

Continuing Investigations of the Relationship between Fin Whales, Zooplankton Concentrations and Hydrothermal Venting on the Juan de Fuca Ridge

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LONG-TERM GOALS

We are investigating the potential correlation between fin whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge. Our goal is to understand the influences of globally distributed hydrothermal plumes on the trophic ecology of the deep ocean.

OBJECTIVES

We are continuing a study of seismic and bio-acoustical data sets from the Juan de Fuca Ridge with the following three objectives:

1. Complete the tracking and detailed analysis of a data set of several hundred thousand fin whale calls recorded on the Endeavour segment over a 3-year period from 2003-2006.
2. Determine whale call counts for ocean bottom seismometers deployed at mid-plate locations on the Explorer and Juan de Fuca plates and near the continental margin in order to test whether the density of vocalizing fin whales is unusually high around the Endeavour vent fields.
3. Complete the calibration of Acoustic Doppler Current Profiler (ADCP) backscatter intensities in terms of biomass and apply the results to historical and NEPTUNE Canada ADCP data to understand the relationship between the seasonal migration patterns of zooplankton and their enhanced concentrations within the water column above the hydrothermal vents.

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APPROACH

The W. M. Keck Foundation supported an experiment on the Endeavour segment of the Juan de Fuca Ridge that included a network of eight ocean bottom seismometers (OBSs) that operated from 2003-6. The experiment also included one-year deployments of OBSs on the Explorer plate and the continental slope offshore Nootka Sound (Fig. 1). More recently, NEPTUNE Canada has commenced seismic observations at 4 nodes on their cabled observatory including the Endeavour segment (Fig. 1). The OBS records include a very extensive data set of fin and, to a lesser extent, blue whale vocalizations. Previous work (e.g., McDonald *et al.*, 1995; Rebull *et al.*, 2006) has shown that seafloor seismic networks can be used to track fin whales but the data sets have been limited to a few tracks. Our approach to analyzing the Endeavour network data is to develop an automatic tracking algorithm (Wilcock, 2012) that picks times of direct and multipath arrivals based on finding peaks in the instantaneous amplitude of the seismic records and uses a grid search approach to find the location that matches the observed arrival times best. The whale tracks can then be combined with calling patterns determined using a matched filter or spectrogram cross-correlation detector to investigate the behavior of vocalizing whales and their distribution relative to the vent fields. To determine call densities from call counts on single isolated OBSs requires a method to estimate the range of calls. To accomplish this we estimate the fin whale source levels using calls located with the Endeavour network. The spacing and amplitude of multipath arrivals on a single station can then be used to determine the range.

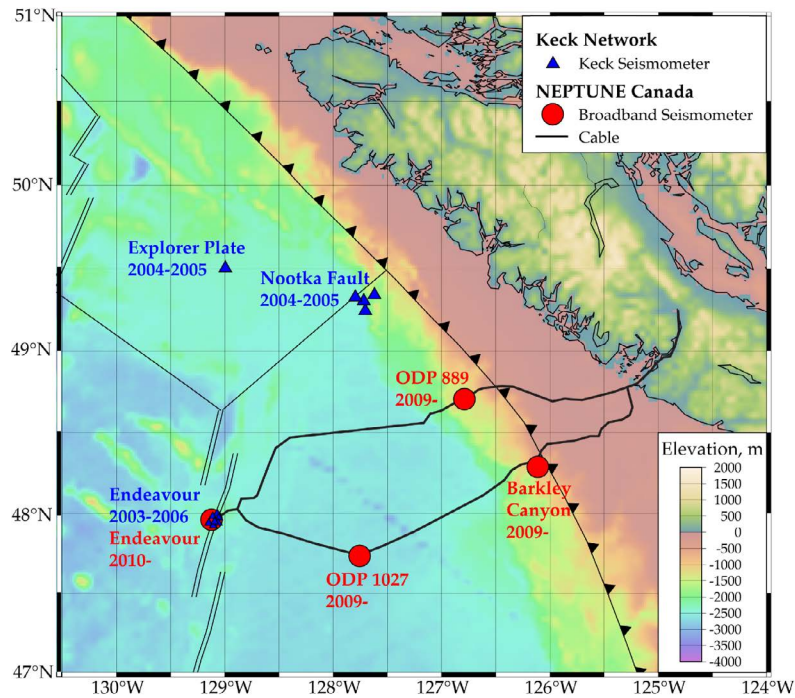


Fig. 1. Map of the NE Pacific Ocean off Vancouver Island showing the locations of seismometers deployed in the Keck experiment and broadband seismometers on the NEPTUNE Canada cabled observatory.

In the early to mid-1990s, the Institute of Ocean Sciences in Sidney, BC conducted summer cruises to the Endeavour to collect a series of plankton net tows in conjunction with measurements including acoustic backscatter intensity. The prior analysis of net samples collected in 1991-4 shows enhanced zooplankton concentrations at all depths above the hydrothermal vent fields (Burd and Thomson, 1994, 1995). At depth, the zooplankton are concentrated in a layer of increased acoustic backscatter near the top of the hydrothermal plume (Thomson *et al.*, 1991; Burd *et al.*, 1992), leading to the inference that the zooplankton are grazing on the plumes. Community analysis shows that the deep faunal assemblages above the vents are infiltrated by shallow species which presumably migrate vertically between the upper ocean and the hydrothermal plume (Burd and Thomson, 1994, 1995). Our approach is to analyze additional net samples collected in the area from 1995-6 to identify major zooplankton and fish species and determine length, gender, stage of development, and dry/wet biomass. The expanded zooplankton data set can be used to refine our understanding of variations in zooplankton concentrations with distance from the hydrothermal vent fields. The data on zooplankton distribution and biomass in the water column overlying Endeavour Ridge are well suited to acoustic calibration of net samples because the ADCP was mounted just below the multiple-net apparatus and the attitude sensors and current measuring capabilities of the ADCP allowed us to determine the flow volume with only 2 to 3% error (Burd and Thomson, 1993). A close regressional relationship between the biomass and acoustic backscatter (for the specified scattering cross-sectional model) means that profile acoustic data can be used to map three-dimensional distributions of biomass in the vicinity of the ridge without the need for expensive and labor intensive net sampling tows. The relationship can be used to interpret upward looking ADCP data collected in the Axial Valley with autonomous instruments deployed from 2003-6 and with the NEPTUNE Canada cabled observatory starting in 2010.

WORK COMPLETED

1. *Whale Tracking*. In previous reporting periods, we described and arrival time picking and locating algorithm for fin whales, investigated the incorporation of additional constraints from amplitude and particle motions, and demonstrated the use of a cross-correlation and double difference method (Waldhauser and Ellsworth, 2000) to refine tracks. These techniques are described article for the *Journal of the Acoustical Society of America (JASA)* that is in press (Wilcock, 2012). We obtained >150 fin whale tracks for 2003-4 ranging in duration from one hour to nearly one day, developed a supervised spectrogram-based method to detect fin whale calls along the tracks, and analyzed the results for call characteristics, calling patterns, swimming patterns, net seasonal migration and spatial distribution. In this reporting period, Graduate student, Dax Soule obtained his MS degree for this work and submitted a manuscript to the *JASA* (Soule and Wilcock, 2012) that is currently in revision.

2. *Whale Call Densities*. In previous reporting periods, we evaluated two automated methods to detect fin calls using matched filters and spectral cross-correlation (Weirathmueller *et al.*, 2011) and obtained call counts normalized to a uniform background noise level for sites on the Endeavour ridge, Nootka fault and middle of the Explorer and Juan de Fuca plates (Fig. 1). In this reporting period we have been working towards our goal of interpreting the observed call counts in terms of call densities. This requires an understanding of the distance at which calls are detected which is influenced by the call source levels and by the effects of water depth and seafloor characteristics on sound propagation. Graduate Student, Michelle Weirathmueller has completed a study of fin whale source levels which has been accepted for publication subject to revisions by *JASA* (Weirathmueller *et al.*, 2012) and is developing a method to pick fin whale arrivals from a spectrogram using cross-correlation and model multipath spacing in terms of the horizontal distance to the fin whale.

3. *Net Sample and ADCP analysis.* In previous reporting periods, we analyzed over 50 net samples collected in 1995-6 for species, gender, age, and net biomass (wet and dry weight) and processed all the acoustic backscatter, water property, and flow velocity data collected during towed ADCP/CTD/Optics/Tucker trawl surveys near Endeavour Ridge in 1995-6 to add to the 1991-4 historical database. We also examined acoustic backscatter time series collected from 2003-6 by upward looking ADCPs moored at several sites within the axial valley. Brenda Burd and Rick Thomson used simultaneous acoustic backscatter and net tow data from 1991-6 to obtain a calibration of the acoustic observations. This calibration is described in an article in *Oceanography* (Burd and Thomson, 2012). In this reporting period, all existing ADCP backscatter and net biomass data have been aligned taxonomically based upon this empirical model and errors and omissions examined and dealt with, and in some cases re-calibrated. This newly completed work includes the incorporation of ADCP backscatter data from tows which did not have associated net biomass. Although generation of this new database has been time-consuming, the work was necessary for the ensuing in-depth analysis of spatial zooplankton biomass and production patterns in the water column relative to the hydrothermal venting sites and to the vertical water property structure. In addition, all net and ADCP tow data have now been accurately geo-referenced, enabling us to conduct detailed examinations of zooplankton biomass as functions of location and depth within the water column.

Progress on the analysis of the NEPTUNE Canada ADCP data has been slowed by repeated logistical problems encountered by the NEPTUNE Canada cabled observatory. Most recently, a NEPTUNE Canada cruise to the Endeavour in September 2012 was cancelled because of the breakdown of the R/V Thompson. As a consequence, work during the present reporting period has been confined to the current, temperature, salinity, and acoustic backscatter time series from two of the four moorings

RESULTS

1. *Whale Tracking.* In the past year we have worked to improve the automation of the tracking algorithm and have picking arrival times for the 2nd and 3rd years of Endeavour data using the instantaneous amplitude method. We will compare these picks with those determined using an alternative spectrogram cross-correlation method (see below) before obtaining tracks.

2. *Whale Call Densities.* Our work over the past year has focused on estimating fin whale source levels and developing a technique to determine the range to a calling whale with a single OBS. Only a few measurements of the source levels of fin whale calls have been published (Charif *et al.*, 2002; Sirovic *et al.*, 2007). The source level is the sum of the transmission losses along the acoustic propagation path and the received level in decibels and its estimation requires good knowledge of the source location. We estimated source levels using calls along the tracks we obtained on the Endeavour segment. To avoid complications due to interactions with the seafloor, only direct path arrivals were analyzed.

Received levels in dB re 1uPa were calculated using the vertical channel of the OBS. The OBS records ground velocity and this was converted to acoustic pressure level using the Zoeppritz equations (Ikelle and Amundsen, 2005). The Zoeppritz equations become unstable as the angle of incidence approaches the critical angle at the seafloor and so we restricted our analysis to incidence angles less than 20°. We determined an average source level of 189.9 ± 5.8 dB re 1uPa @ 1m from a total of 1241 calls.

Errors in source level estimates arise from the 300-500 m uncertainties in the position of the whales and from unknown uncertainties in the assumed source depth of 50 m which is based on a single estimate in the literature (Watkins *et al.*, 1987). The direct path and the first surface bounce overlap and depending on the depth of the whale, this can result in constructive or destructive interference. The uncertainty in horizontal position affects the transmission loss calculation, but the larger effect is due to the uncertainty introduced into the incidence angle estimate, which is required for the Zoeppritz calculations. A model was created to simulate the potential errors arising from the combination of these effects (Fig. 2). The source levels simulated using the model showed a variability that is comparable to estimated source levels when the true source level was itself assumed to vary with a standard deviation of 4 dB (Fig. 3).

A small number of track segments contained sufficient consecutive calls to investigate source level variations between gaps in calling that are assumed to mark the start and ends of dives. Although individual tracks often showed small systematic variations in source levels over a dive, the sign of the trend was inconsistent; estimated source levels were equally likely to increase or decrease during a dive. The trends within individual tracks most likely arise from systematic errors in call location rather than changes in source level.

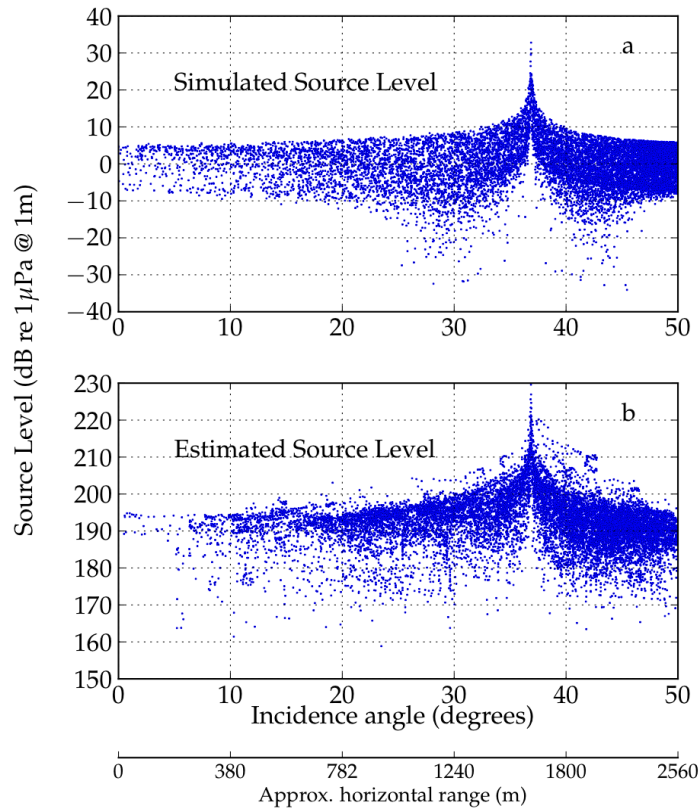


Fig 2. (a) Model source level output for an input source level of 0dB. (b) Source levels estimated from data. Both are plotted versus incidence angle, but a second X-axis shows approximate range for a call generated at 50 m depth and a total water depth of 2200 m.

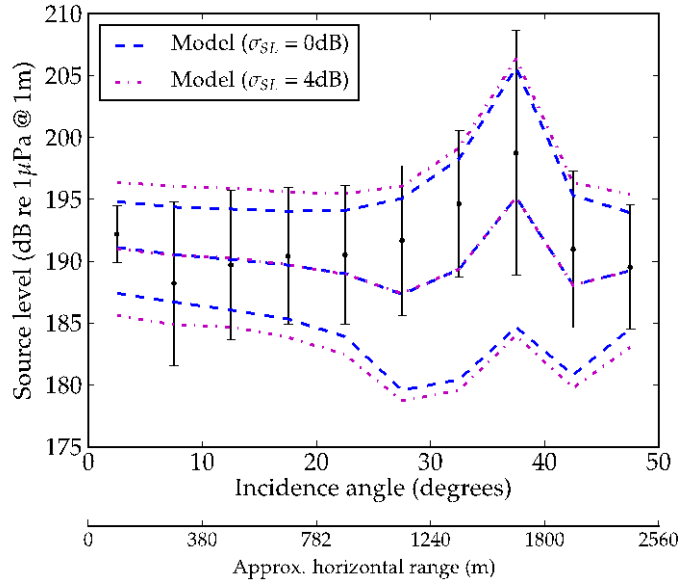


Fig 3. Comparison of the variability between the measured source levels (plotted as circles with error bars indicating the mean and standard deviation in incidence angle bins of 5°) and simulated source levels for a uniform source (blue dashed lines at the mean and 1-s levels) and a source with a variability of 4 dB (red dot-dashed line). The simulation model the effects of uncertainties in the horizontal and vertical position of the whale.

For isolated OBSs, ranges can be estimated using the relative arrival times of the direct and multipath arrivals (McDonald and Fox, 1999; Sirovic *et al.*, 2007) with source levels used to predict received levels and ensure that arrival times are correctly associated with the correct multipath. We have developed an automatic algorithm based on spectrogram cross correlation to detect direct and multipath arrivals originating from single calls. An acoustic propagation model was used to predict arrival times for ranges up to 25 km, assuming a flat seafloor and an average sound speed profile. Simulated signals were generated using Gaussian functions centered on predicted and measured arrival times. The predicted and measured signals were then cross-correlated with each other and the estimated corresponding to the maximum in the cross-correlated output. Fig. 4 shows two examples of ranges estimated using this method. We are also evaluating this algorithm as an alternative means of picking arrivals for the tracking algorithm that will be applied to the 2nd and 3rd years of Endeavour network data.

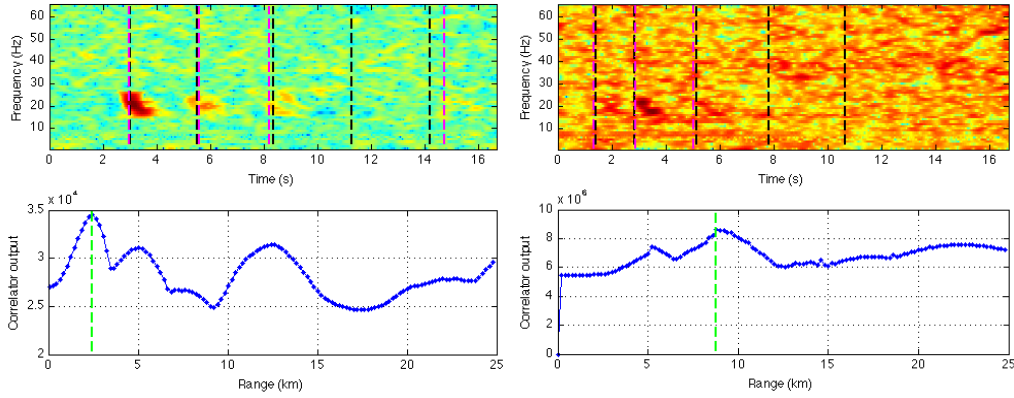


Fig. 4. Estimates of range obtained from a single OBS using the multipath method for whales at estimated ranges of (left) 2.4 km and (right) 8.8 km. The upper plots show the spectrogram with arrival times picked by and automatic spectrogram cross-correlation detector in magenta and the modeled times for the estimated range in black. The lower plots show the output obtained by correlating observed times with predicted times for different ranges with observed times, Green dashed lines indicate range of the maximum correlation value.

ADCP and Net Tow analysis. Burd and Thomson (1994) used net samples from the 1991 and 1992 tows to provide a preliminary examination of the mean zooplankton biomass density in relation to distance from the vent fields. That relationship has now been examined for: (1) all net-tow data from 1991-1996 (35 tows); and (2) all ADCP backscatter data collected in those years (39 tows), including downcast and upcast profiling data.

The ADCP/net apparatus was not towed at a consistent upward rate since we were often “hunting” for features such as the hydrothermal plume. Therefore, there is not a consistent tow duration for all nets or depth ranges. For this reason, average biomass density in the water column was estimated by weighting density values for different depth ranges. For nets, weighting was based on the depth range for each net (average biomass density multiplied by the fraction of the total depth range encompassed by a given net at that tow location). For the ADCP data, which is more continuous (every 30 seconds), we can specify the depth ranges for ADCP-derived biomass estimates (which, in turn, are based on the backscatter-to-biomass calibration curve published in Burd and Thomson, 2012). The selected depths are presently considered to encompass specific hydrographic features, as follows:

- (1) 0-100 m (upper photic zone above the steep permanent pycnocline/thermocline that begins around 100 m depth in the northeast Pacific);
- (2) 100-400 m (migratory range for most upper ocean fauna);
- (3) 400-800 m (depth range for the mid-depth scattering layer, consisting largely of diapausing or reproductive copepods and their associated predators); 800 m is also the approximate depth of the oxygen minimum layer in the northeast Pacific;
- (4) 800-1600 m (low biomass depth range within and below the oxygen minimum layer, otherwise showing relatively uniform water property structure);

- (5) >1600 m (including, if present, the deep scattering layer and the hydrothermal plume; otherwise this abyssal depth range typically has uniform water properties).

Fig. 5 shows a comparison of the mean weighted biomass density obtained from the nets and from conversion of the ADCP backscatter intensity for the full water column. The net-derived results show a clear decline in biomass density with distance from the main vent fields; no such decline is readily apparent in the ADCP biomass estimates. Net data from which all gelatinous animals (Cnidaria, Urochordata) have been removed shows the same pattern as the total net data, with a slight downward shift.

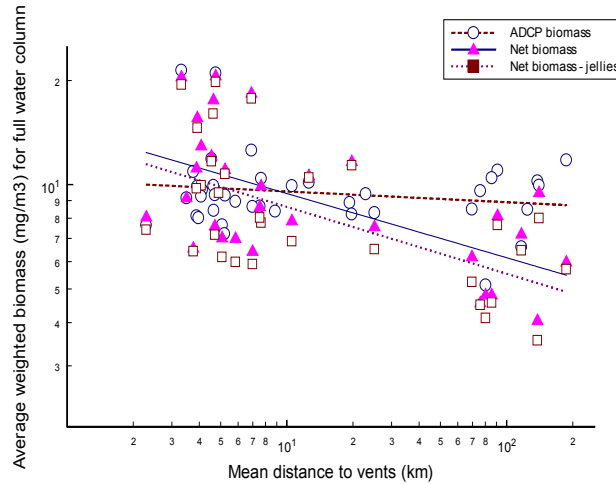


Fig. 5. Mean depth-weighted biomass density for the full water column tows based on: (1) the total net biomass; (2) the net biomass without gelatinous organisms; and (3) the ADCP biomass estimates derived from the acoustic backscatter intensity (Burd and Thomson, 2012). Average biomass density based on the nets show a clear decline with distance from venting locations, whereas the ADCP-derived biomass estimates do not.

Fig. 6 provides a comparison of the acoustic biomass densities for two major depth ranges (>800 m and <800 m). There is no discernable difference in biomass with distance from vents in the upper ocean, but below 800 m, a decline with distance is evident in nets (see Fig. 5). This pattern is even clearer for ADCP-derived biomass data for depths >1600 m (not shown because of space limitations).

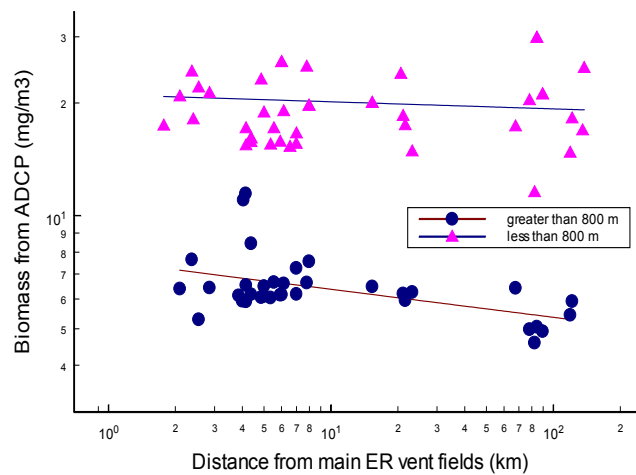


Fig. 6. ADCP-derived biomass density estimates for summed ensembles from < 800 m depth (pink filled triangles) and > 800 m depth (blue filled circles). Biomass density was typically much lower in the deep ocean, but was higher near the active vents (< 20 km distance) than off-axis (> 70 km distance).

IMPACT/APPLICATIONS

We have developed automatic fin whale detection and tracking algorithms that can be applied to other seafloor seismic networks. The location method could be applied to other vocalizing species (or anthropogenic sounds) with a network of seafloor receivers provided the calls are sufficiently short and spaced far enough apart so that the direct and multiple arrivals do not overlap. The double difference method is commonly used in earthquake studies but has not previously been applied to marine mammals. The close relationship between biomass and acoustic backscatter provides a method to extrapolate limited net tow data to images of the 3-D distribution of biomass. If a correlation is found between the distribution of whales, enhanced zooplankton concentrations and hydrothermal vents it will have implications for our understanding of the global influences of hydrothermal vents on the trophic ecology of the ocean (Gisiner *et al.*, 2009).

RELATED PROJECTS

The Endeavour node on the NEPTUNE Canada regional cabled observatory is slowly being populated by water column experiments that will monitor deep macrozooplankton concentrations (Rick Thomson is the lead-PI) and by a seafloor seismic network (William Wilcock is a co-PI). The amphibious portion of Cascadia Initiative is an ambitious NSF project that will from 2011-2015 deploy 70 OBSs at ~160 sites over the Juan de Fuca plate and Cascadia margin from approximately 40°N to 50°N, thus providing the opportunity to investigate the broader spatial and temporal distribution of fin and blue whales.

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